

Scoping analysis of the potential yield of the Hollandse Kust (zuid) wind farm sites and the influence on the existing wind farms in the proximity

B.H. Bulder

E.T.G. Bot

A.J Marina

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Abstract¹

The potential energy yield of and the influence of the Hollandse Kust (zuid) (HKZ) Wind Farm Zone on the energy production of the existing wind farms, Luchterduinen, Prinses Amalia and OWEZ is calculated with FARMFLOW, ECN's wind farm aerodynamic performance analysis tool.

The HKZ wind farm zone consists of 4 sites and each site is designated to be developed with a 350 MW off shore wind farm. The sites I & II will be tendered to the developers in 2017 while site III & IV will be tendered in 2018. It is decided that all sites will have a guaranteed nominal power of 350 MW but the development plan can go up to 380 MW per site. The export transmission system will have a guaranteed capacity to transmit at least 350 MW to the national grid on shore. However, under normal conditions, the transmission system is capable to transmit the generated power – minus the internal electrical losses to the national grid. Only when the export cable core temperature increases above a limit temperature the output of the site will be curtailed to 350 MW.

For each site, I – IV, in the HKZ wind farm zone, 2 designs have been made. One design consisting of 6 MW wind turbines with a rotor diameter of 154 m and one design consisting of 8 MW wind turbines with a rotor diameter of 164 m. For each of the sites the potential energy production has been calculated and the influence of site I & II and site I – IV, is determined on the production of the existing wind farms.

For this report the reference consist of the 3 existing wind farms in the neighbourhood:

- Wind Farm Luchterduinen, consisting of 43 Vestas V112, 3 MW wind turbines;
- Wind Farm Prinses Amalia, consisting of 60 Vestas V80, 2 MW wind turbines and
- Wind Farm OWEZ, consisting of 36 Vestas V90, 3 MW wind turbines.

The wind resources have been determined at three corner locations; the wind resources for the wind farm considered have been interpolated.

The potential energy yield has been determined for the reference case and for:

- HKZ site I & II without and with the reference wind farms;
- HKZ site I, II, III & IV without and with the reference wind farms;

In each case the effects wake losses have been determined for all wind farms in the case. The maximum loss predicted is for the Luchterduinen wind farm is 7.8%.

For simplicity no losses due to the internal electrical losses and losses due to availability and losses or due to environmental requirements are taken into account.

¹ Due to errors in table 5 and 6 the second edition of this report is published

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1

Introduction

In assignment of the ministry of Economic Affairs of the Netherlands, a quick scan study has been performed to predict the performance of planned and existing wind farms near the Hollandse Kust (HK) Wind Farm Zone.

The Hollandse Kust wind farm zone has been split up in two parts, Hollandse Kust Wind Farm Zone zuid (HKZ) and noord (HKN). In this report the influence of and the potential energy yield of the Hollandse Kust zuid wind farm zone is reported.

The HKZ wind farm zone consist of 4 sites that each will be developed for a 350 MW offshore wind farm. The sites will be tendered to offshore wind farm developers in two consecutive years, site I & II in 2017 and site III & IV in 2018.

Finally an estimation has been made what the effect on wind farm efficiency will be when the nominal power is increased to 2100 MW and what will be the effect on the wind farm efficiency when the available area for the HKZ wind farms will be reduced with the area within the 12 mile zone.

The wind resources at the locations have been determined on the basis of the HiRLAM database that ECN acquired over the years 2002 – 2013, so 12 years of wind predictions. The wind resources have been correlated with measurements at the meteo mast IJmuiden ver.

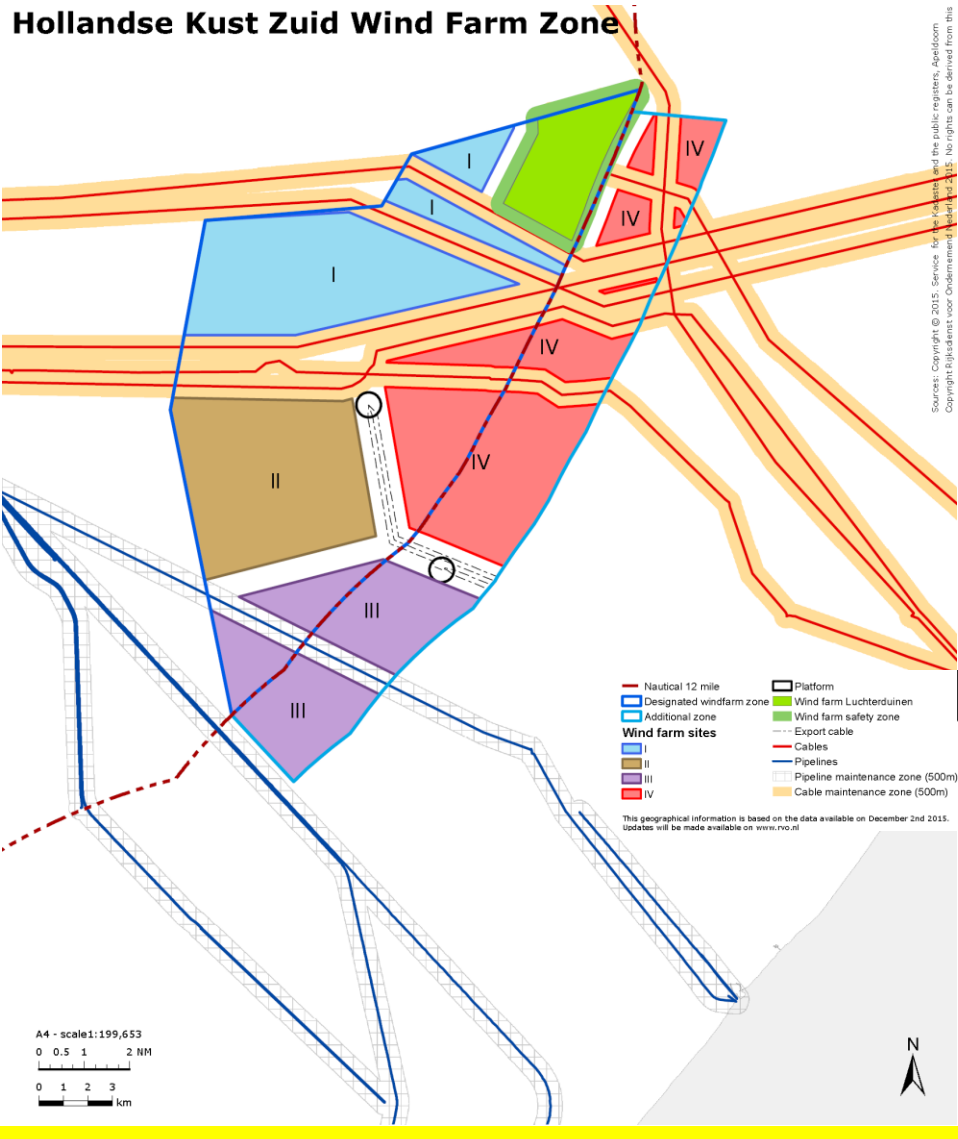
For each site two different wind farm designs have been made, one with a 6 MW wind turbine and one with an 8 MW wind turbine. For each site and design the potential energy yield has been determined where the yield of site I & II is determined and the yield of site I – IV have been determined. Next to that the energy yield of the sites I & II and site I – IV have been determined taking the existing wind farms into account.

The existing wind farms are:

- Wind Farm Luchterduinen, consisting of 43 Vestas v112, 3 MW wind turbines;
- Wind Farm Prinses Amalia, consisting of 60 Vestas V80, 2 MW wind turbines and
- Wind Farm OWEZ, consisting of 36 Vestas V90, 3 MW wind turbines.

The energy yield of the existing wind farms, without any of the new wind farms has been calculated to determine the additional wake losses due to site I & II and site I – IV.

For each site of the KHZ Wind Farm Zone, 2 different designs are made assuming the maximum allowable overplanting, to the closest value of 380 MW, as shown in **Table 1**



Both questions will be dealt with on the basis of results of a design variation calculated for the Borssele area, see report [2].

Table 1: The characteristics of the wind farm designs created for site I - IV

Wind farm		WT P_{rated}	rotor density	Number	Nominal Power
Site design		[MW]	$[W/m^2]$	of WT's	Wind Farm
					[MW]
I	A	6	320	63	378
	B	8	380	47	376
II	A	6	320	63	378
	B	8	380	47	376
III	A	6	320	63	378
	B	8	380	47	376
IV	A	6	320	63	378
	B	8	380	47	376

For each site the potential energy yield, the capacity factor and the wind farm efficiency is determined.

The following tasks are performed to determine these effects:

- Task 1. Create the wind farm site designs for both turbine types.
- Task 2. Model the reference wind farms, Luchterduinen, Prinses Amalia and OWEZ
- Task 3. Determine the wind conditions for the HK wind farm zone by determining the wind roses at a centre location of an area enclosing the HK wind farm zone. The wind resources will be determined at 100 m above MSL that will be interpolated to the location of each wind farm and interpolated to the hub height of the wind farm considered.
- Task 4. Calculate the wind farm yields for both turbines types
 - a. For the reference situation, only the existing wind farms, OWEZ, Prinses Amalia and Luchterduinen;
 - b. For site I & II together, without the existing wind farms;
 - c. For site I & II together, including the existing wind farms;
 - d. For site I, II, III & IV together, without the existing wind farms;
 - e. For site I, II, III & IV together, including the existing wind farms;
- Task 5. Calculate the wind farm efficiencies and capacity factors for each site for both turbine types;
- Task 6. Calculate the additional losses for the existing wind farms due to the new wind farms, site I & II and site I, II, III & IV for both turbine types.

The results of the designs and calculations can be found in this report.

1.1 The wind turbine models

For the HKZ wind farms two different wind turbines models are used, one with a rated power of 6 MW and one with a rated power of 8 MW. The rotor power density, i.e. the ratio of the rated power over the rotor area, was also different between the two wind turbines. The 6 MW design has a rotor power density of approximately 320 W/m^2 and the 8 MW model has a rotor power density of approx. 380 W/m^2 . This resulted in an 8 MW wind turbine with a rotor diameter of 164 m and a 6 MW wind turbine with a rotor diameter of 154 m.

The existing wind farms are modelled on the basis of lay-out information received from the Ministry of Economic Affairs and the turbine characteristics on the basis of publicly available data, power curve and thrust coefficient curve.

The characteristics of the virtual wind turbine models used in the analysis can be found in Appendix A.

The characteristics of the wind turbines used in the existing wind farms can also found in Appendix A.

1.2 The wind farms designs

The HK Zuid wind farms

Due to the fact that the wind farms HKZ are still in the planning phase and consequently not yet designed, two designs have been made for each site where the spacing of the wind turbines is as large as possible to reduce wake effects and not taking (local) conditions as e.g. water depth into account.

All design created; do take into account that the rotor blades should stay inside the contours of the sites. Thus the foundations are all at least half a diameter from the site boundary.

The designs are shown in the following figure, **Figure 2**

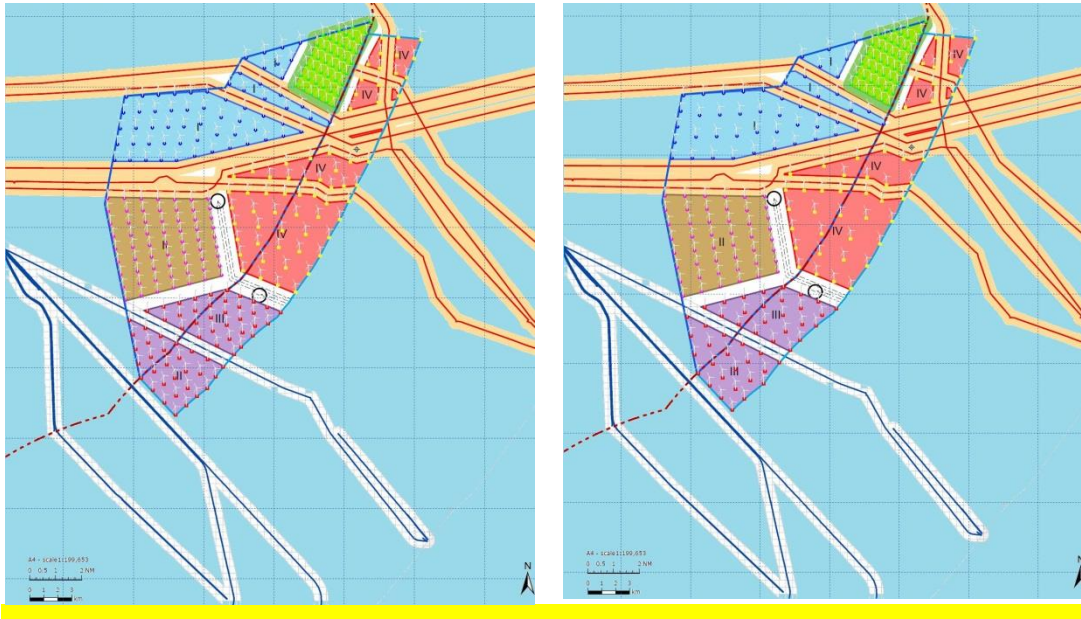


Figure 2: The HKZ wind farm zone, including OWF Luchterduinen, with 6 MW wind turbines, left, and 8 MW wind turbines (right).

Existing wind farms

The existing wind farms are modelled in FARMFLOW on the basis of the information received from the Ministry of Economic affairs, see **Figure 3**



Figure 3: The HKZ wind farms, enclosing OWF Luchterduinen and showing the location of the OWF Prinses Amalia (yellow) and OWEZ, on the left the HKZ with 6 MW wind turbines and on the right with 8 MW wind turbines.

Table 2: The existing offshore wind farms information on the www.4coffshore.com website.

Project	Build/commission date/	Wind Farm Area	P _{rated} WT	D _{rotor}	H _{hub}	Nominal WF power	# WT's
		Km ²	MW	m	m	MW	
OWEZ	2006	24	3	90	70	108	36
Prinses Amalia	2006 - 2008	14	2	80	59	120	60
Luchterduinen	2014-2015.	16	3	112	81	129	43

1.3 The undisturbed wind rose at the HK Wind Farm Zone.

The wind conditions at the HK Wind Farm zone are based on a database of wind conditions maintained by ECN. A full period of 12 years, 2002 – 2013, has been used to derive the wind data. Three corner points are selected and for each point the wind rose is determined with 12 years of HiRLAM data. Next to that the HiRLAM data base has been evaluated for the years 2012 and 2013 at the IJmuiden ver meteo mast location at an altitude of 90 m. The average wind speeds have been correlated to determine a factor between the “real” measured wind and the by HiRLAM predicted wind speed. The wind roses have been multiplied with this factor to make the wind roses at the corner points. The average of the three wind roses is shown in **Table 3**

The wind rose at 100 m height is given in **Table 3**

Table 3: The Weibull data for 12 sectors at a height of 100 m.

	Sector	Frequency	Weibull A	Weibull k	Wind speed	Power density
	[-]	[%]	[m/s]	[-]	[m/s]	[W/m ²]
1	N	7.54	8.84	2.40	7.84	480.79
2	NNE	5.26	8.74	2.40	7.75	464.10
3	NEE	7.04	9.26	2.70	8.23	512.48
4	E	6.68	8.53	2.90	7.61	387.32
5	SEE	4.99	8.32	2.50	7.38	390.27
6	SSE	6.50	9.78	2.70	8.69	603.34
7	S	7.43	11.13	2.40	9.87	956.43
8	SSW	12.54	12.79	2.70	11.38	1348.04
9	SWW	12.52	11.34	2.50	10.06	983.19
10	W	10.05	9.98	2.40	8.85	691.53
11	NWW	10.36	10.19	2.30	9.03	759.21
12	NNW	9.08	9.57	2.00	8.48	713.81
	All	99.99	10.18	2.48	9.03	757.55

1.4 The wind farm wake analysis

The wind farm wake analysis is performed with ECN's FARMFLOW model. The FARMFLOW model is developed by ECN to predict the wind turbine wake effects of offshore wind farms. The tool comprises a wake model that has been verified with measurements and compared to other models in numerous (benchmark) projects. See Appendix B for a more extensive description of the model and the verification documents.

1.5 The results

The results of the analysis are the gross P_{50} energy yield after subtracting the wake losses of the existing wind farms without and with the new wind farms present. The difference between the yields of the two situations is the additional energy losses due to the presence of the HKZ site I & II and HKZ site I – IV, wind farms.

Next to that also the energy yields of the HKZ site I & II with the 6 and the 8 MW wind turbines are determined and the energy yield of the HKZ site I – IV are calculated for both turbine types.

2

The wind farm designs

2.1 The existing wind farms

OWEZ

The OWEZ wind farm is the first Dutch offshore wind farm in the North Sea. The OWEZ wind farm has a rated power of 108 MW and it comprises of 36 Vestas V90 3 MW wind turbines. Its location is near the town of Egmond aan Zee.

Prinses Amalia

The prinses Amalia wind farm, located just south west of the OWEZ wind farm. The wind farm has a rated power of 120 MW and consists of 60 Vestas V80 2 MW wind turbines.

Luchterduinen

The Luchterduinen Offshore Wind Farm is encapsulated by the HKZ WF zone. The wind farm has a rated power of 129 MW and has 43 Vestas V112 3 MW wind turbines.

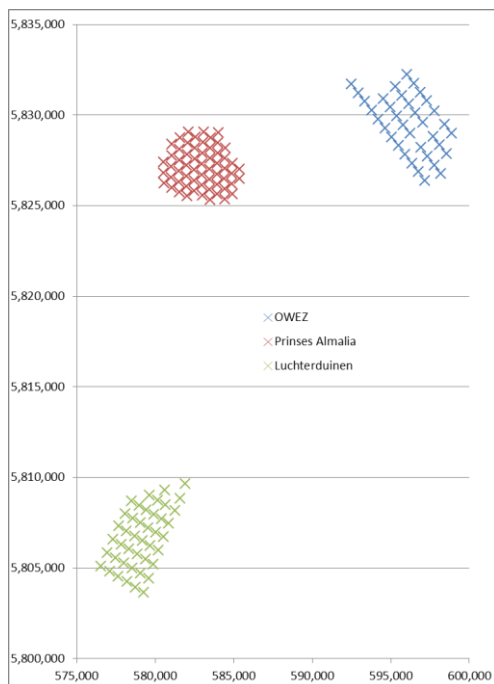


Figure 4: The lay out of the existing wind farms

2.2 The HKZ offshore wind farms

For each of the four sites of the HKZ wind farm zone, 2 different designs are created. It is assumed that all designs should have the maximum number of wind turbines allowed within the given overplanting margin of 380 MW. This results in designs with a nominal power of 376 MW, i.e. 47 x 8 MW wind turbines, and 378 MW, i.e. 63 x 6 MW wind turbines, see **Table 1**. The designs are shown in the **Figure 5 - Figure 12**.

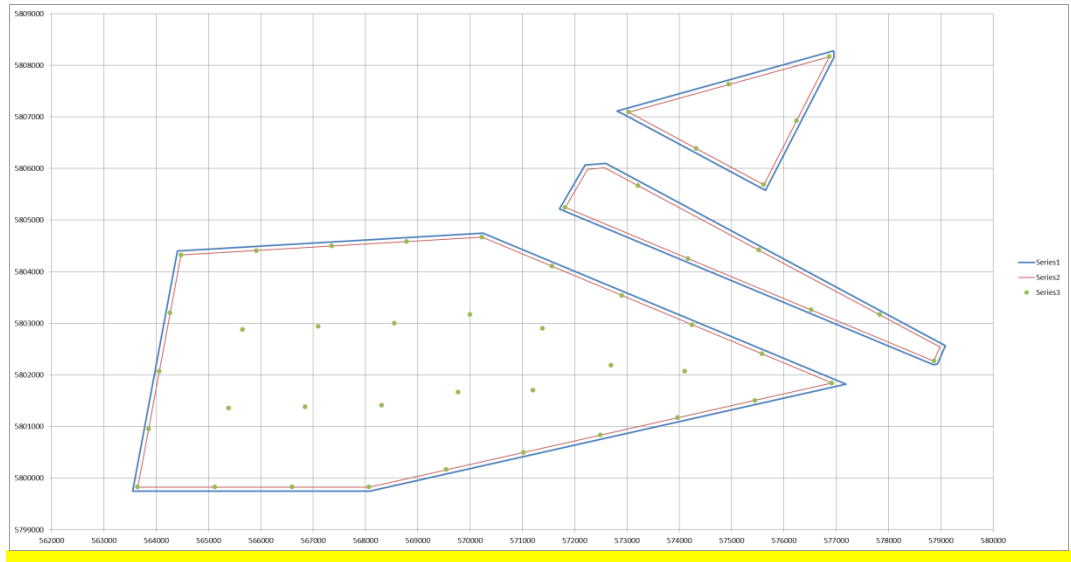


Figure 5: The lay-out of Site I with 8 MW wind turbines

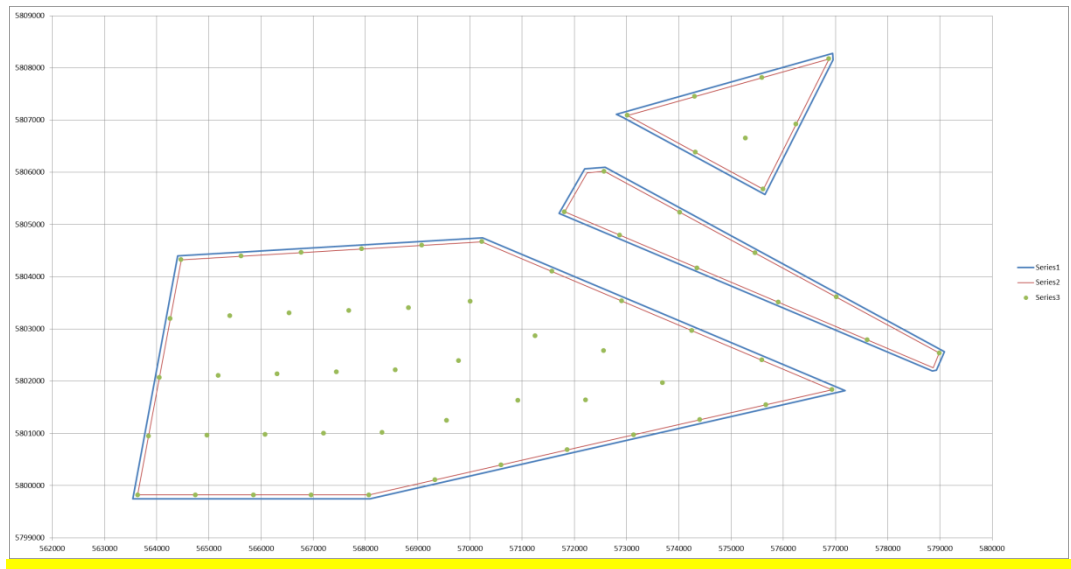


Figure 6: The lay-out of Site I with 6 MW wind turbines

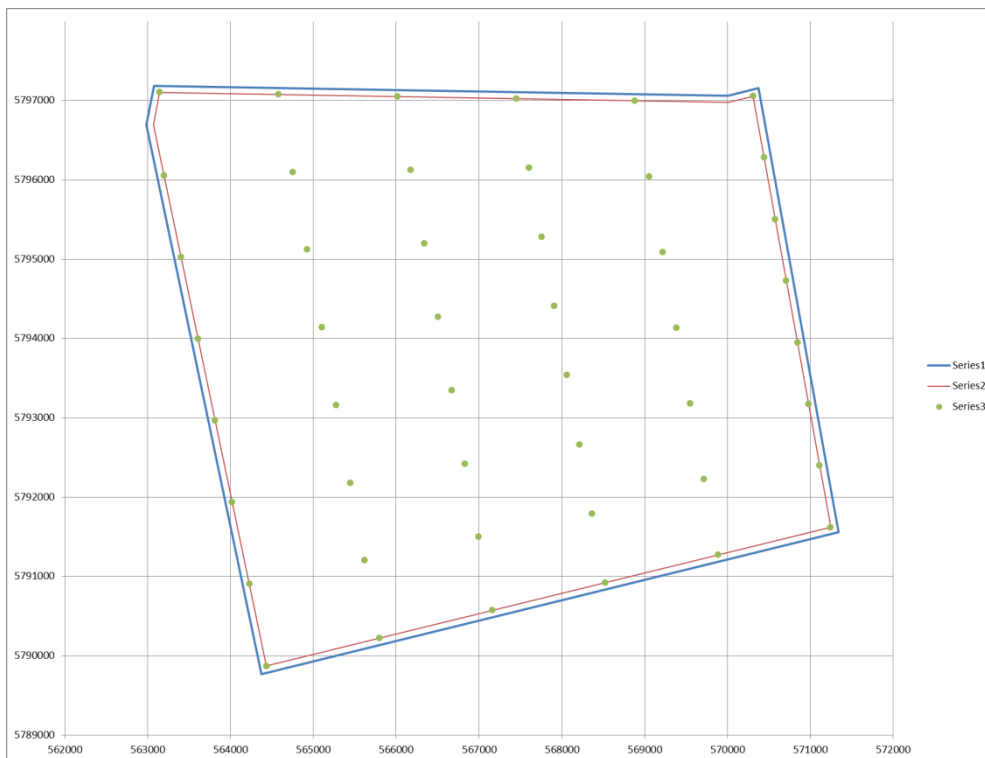


Figure 7: The lay-out of Site II with 8 MW wind turbines

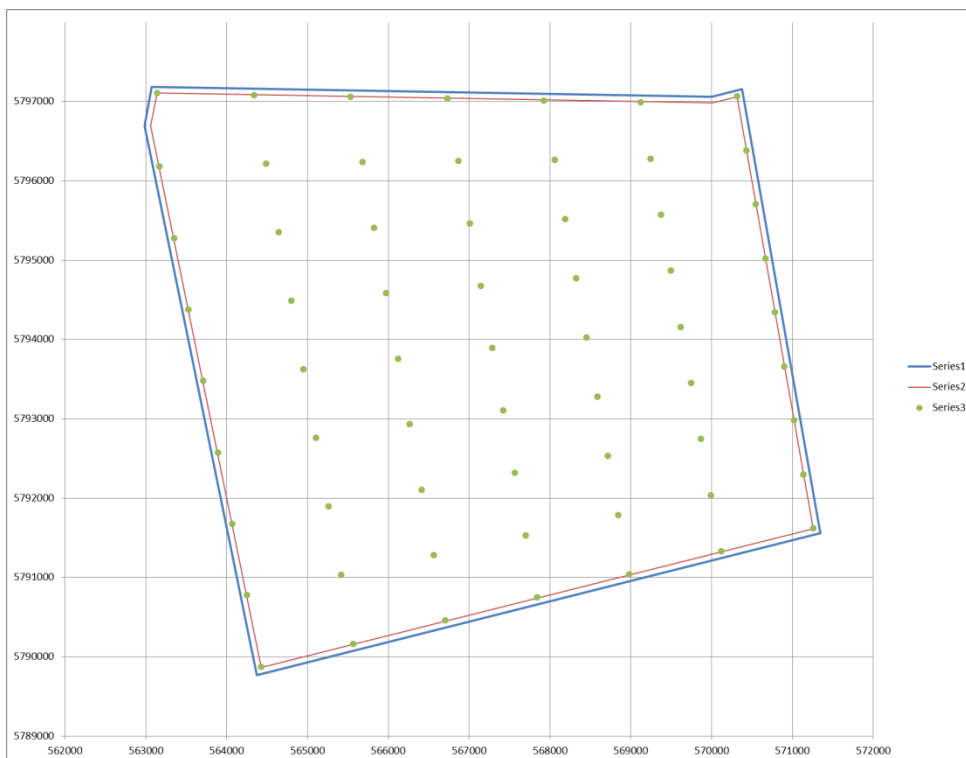


Figure 8: The lay-out of Site II with 6 MW wind turbines

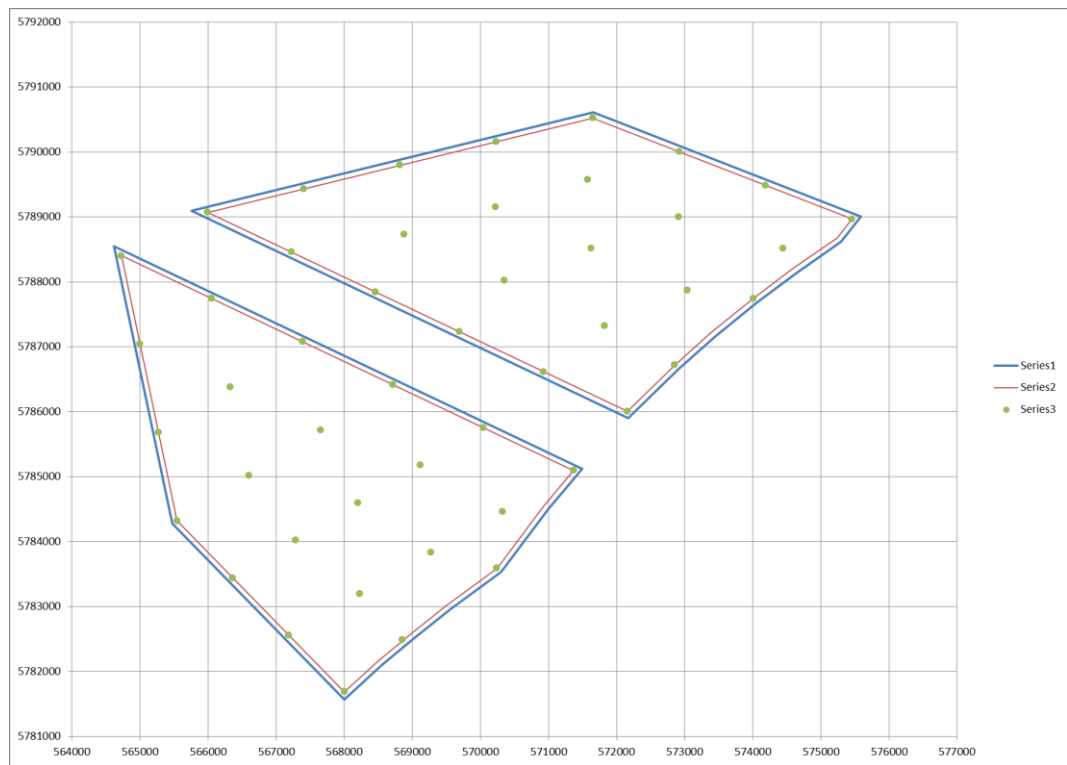


Figure 9: The lay-out of Site III with 8 MW wind turbines



Figure 10: The lay-out of Site III with 6 MW wind turbines

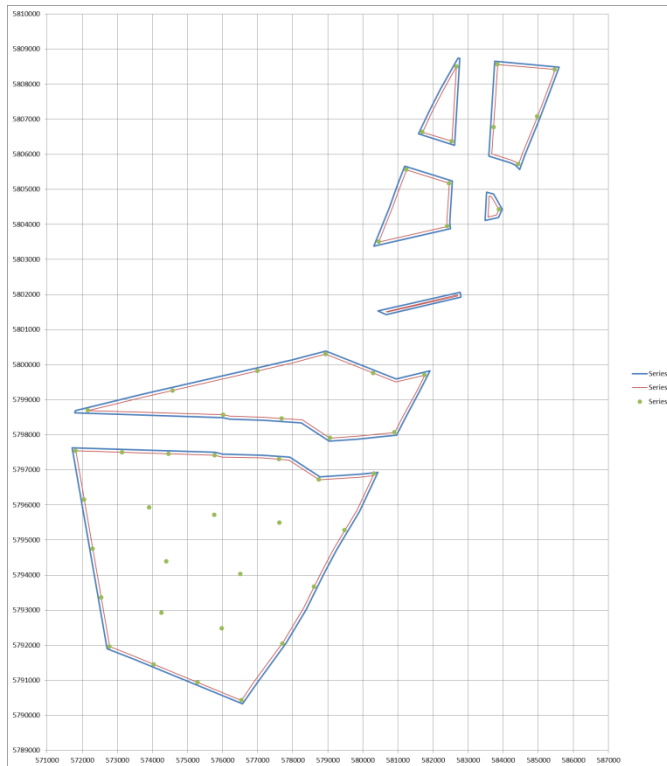


Figure 11: The lay-out of Site IV with 8 MW wind turbines

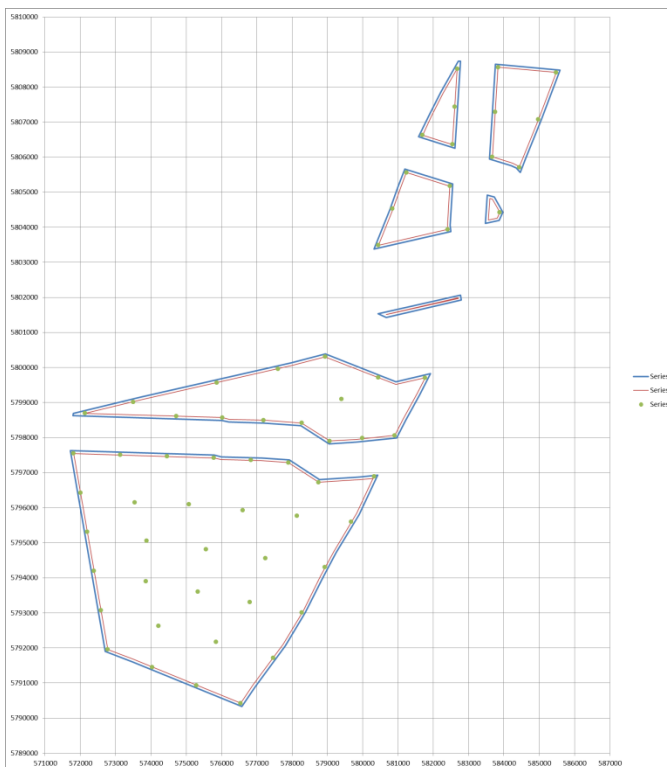


Figure 12: The lay-out of Site IV with 6 MW wind turbines

3

Results

3.1 The yield of the existing wind farms, the baseline case.

The gross yield of the existing offshore wind farms has been calculated with FARMFLOW with and without the presence of the wind farms in the HKZ Wind Farm zone. No losses due to availability of system components or losses due to electrical system are taken into account. Assuming that all losses other than the wake losses have a small influence on the total system performance it is assumed that this is acceptable considering the nature of the study.

The baseline situation is the present situation with only the existing wind farms. The yield and capacity factor calculated is listed per wind farm in

Table 4: The calculated energy yield of the existing wind farms, the baseline case

		OSWF Luchterduinen	OSWF prinses Amalia	OSWF OWEZ
# wt's	[-]	43	60	36
Type of WT		MHI Vestas 112	Vestas 80	Vestas 90
Rated power of the wind farm	[MW]	129	120	108
Energy yield	[GWh]	574611	428210	388446
Capacity factor	[%]	50.81	40.71	41.03
Full load hr's	[hr's]	4451	3566	3594

3.2 The yield of the existing wind farms and the new HKZ site I & II wind farms

The gross yield of the three existing wind farms is recalculated including the HKZ site I & II wind farms for both scenario's, with a 6 MW wind turbine and 8 MW wind turbine, see **Table 5**. The table shows the energy yield for each wind farm and the reduction in yield due to the new wind farms. The additional losses for the Site I & II wind farms are

the losses compared to the yield for Site I & II as if the existing wind farms are not there.

Table 5: The yield of the base line wind farms + HKZ site I & II

		OSWF Luchterduinen		OSWF prinses Amalia		OSWF OWEZ		OFWF HKZSite I		OFWF HKZ Site II	
		6MW	8MW	6MW	8MW	6MW	8MW	6MW	8MW	6MW	8MW
Energy yield	[GWh]	549831	550116	425250	426118	385677	385349	1678134	1579050	1655634	1567168
Capacity factor	[%]	48.62	48.65	40.43	40.51	40.74	40.70	50.64	47.91	49.97	47.55
Additional loss	[%]	4.31	4.26	0.69	0.49	0.71	0.80	1.26	1.43	0.21	0.30

3.3 The yield of the existing wind farms and the new HKZ site I - IV wind farms

The gross yield of the three existing wind farms is recalculated including the HKZ site I & II wind farms for both scenario's, with a 6 MW wind turbine and 8 MW wind turbine, see **Table 6** and **Table 7**.

The table shows the energy yields for all existing wind farms and HKZ site I – IV. The additional losses for the existing wind farms are compared to the baseline situation. The additional losses for the site I&II are compared to the scenario where only site I & II are built and no other wind farms are in the proximity. The additional losses for the Site III & I V are compared to the situation where only HKZ, all sites, are built and the existing wind farms are not there.

Table 6: The yield of the baseline wind farms + HKZ site I - IV with 6 MW, low rotor power density wind turbines

		OSWF Luchter- duinen	OSWF Amalia	OSWF OWEZ	OFWF HKZSite I	OFWF HKZ Site II	OFWF HKZ Site III	OFWF HKZ Site IV
Energy yield	[GWh]	529560	421398	382245	1641544	1587602	1621874	1629908
Capacity factor	[%]	46.83	40.06	40.38	49.54	47.91	48.95	49.19
Additional loss	[%]	7.84	1.59	1.60	3.41	4.31	0.19	1.16

Table 7: The yield of the baseline wind farms + HKZ site I - IV with 8 MW, high rotor power density wind turbines

		OSWF Luchter- duinen	OSWF Amalia	OSWF OWEZ	OFWF HKZSite I	OFWF HKZ Site II	OFWF HKZ Site III	OFWF HKZ Site IV
Energy yield	[GWh]	534702	423865	382803	1550015	1510215	1539109	1539956
Capacity factor	[%]	47.28	40.29	40.43	47.03	45.82	46.70	46.72
Additional loss	[%]	6.95	1.01	1.45	3.25	3.92	0.21	1.31

4

Discussion

4.1 Effects of wind farm power density variations

To investigate the effects of increasing the wind farm power density, e.g. to install more wind turbines at the sites or to reduce the available area the results of a previous study have been used, see [1, 2].

The study [2] resulted in the energy yields for the Borssele site for two different wind farm power densities, 6 and 9 MW/km² and the energy yield and the different wake effects. See **Table 8** for the overall results of the analysis.

Table 8: The nominal power of the Borssele location wind farm and number of wind turbines, based on [2]

Design	Rotor Power density [W/m ²]	Wind farm Power density [MW/km ²]	Nominal power [MW]	Annual Yield [GWh/yr]	Wind Farm Capacity Factor [-]	Wind Farm Efficiency [%]
1	320	9	2340	9731.9	0.475	84.31
2	380	9	2400	9576.9	0.456	86.40
3	320	6	1596	7023.7	0.502	89.22
4	380	6	1600	6761.7	0.478	90.61

Linearizing the effects of power density changes and the wake losses and evaluating the trend line at 1400 MW and at 2100 MW results in a wake effects increase from 8% for a 1400 MW wind farm to 11.5% for a wind farm of 2100 MW. This is a relative increase of 44%.

The gross area of the HKZ wind farm zone, including the area of the Luchterduinen wind farm (16 km²) is 356 km², see [4]. The net area, that is the gross area minus the area

that cannot be used due to cables and pipelines is visually estimated to be $1/3^2$ of the gross area, is $\sim 240 \text{ km}^2$.

From **Figure 1** it is estimated that the available area is reduced by approximately 35% when the area between the 10 and 12 mile zone is not used. The average wind farm power density, based on the gross HKZ area is approximately 4 MW/km^2 , on the net area it is approximately 5.8 MW/km^2 and based on the area outside the 12 mile zone the wind farm power density would be approximately 8.75 MW/km^2 .

The main effect of changing the power density of a wind farm is the change in the internal wake effects and different electrical losses in the wind farm. A higher wind farm power density will result in lower spacing between the wind turbines and will result in higher wake effects and lower electrical losses. In the range of $10 - 4 D$ spacing the total effect is that the wake losses increase faster than the decrease in electrical losses. The wind farm yield and wind farm efficiency decrease substantially. The results of an example from the European Commission funded research project EERA DTOC, FP7-ENERGY-2011-1/ n°282797, is shown in **Figure 13**

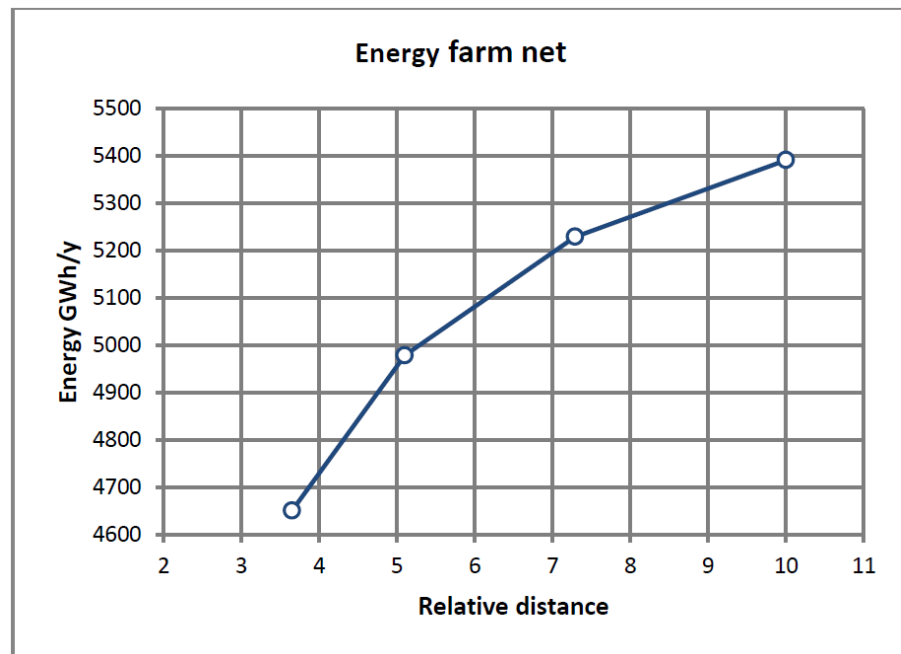


Figure 13: The energy yield of a 1 GW wind farm consisting of a 100 10 MW wind turbines for different inter turbine spacing. Copied from [3].

Without detailed calculation it is assumed that the increase in wake effects due to wind farm power variations at the HKZ wind farm zone is identical to the trends calculated at the Borssele zone.

Thus increasing the installed power from 1400 MW (nominal power) to 2100 MW will increase the wind farm wake losses by approximately 44%.

² The factor is nearly equal to the factor for the Borssele Wind Farm Zone.

By decreasing the area with the 10 – 12 mile zone the effect will be approximately the same, increasing the wake losses by ~ 45%. There is an additional uncertainty in here due to the fact that the power density is increased by reducing the area while in the Borssele study report the power density increase is performed by increasing the number of wind turbines while in the analysis here the available area is reduced.

5

Conclusions

The analysis of the baseline situation shows that the gross energy yield for the existing wind farms will be reduced due to the building and operation of the HKZ wind farms. Not surprisingly the OFWF Luchterduinen will suffer the highest losses, due the fact that the Luchterduinen wind farm is nearly enclosed by the HKZ wind farms.

The maximum calculated loss for the Luchterduinen wind farm is 7.8 %. For the OWEZ wind farm the maximum calculated loss is 1.6% and for the prinses Amalia wind farm the maximum loss is predicted also at 1.6%.

The maximum loss calculated for the Luchterduinen OFWF is 7.8%.

The reason the losses for the OWEZ wind farm, due to the HKZ wind farms, is equal or higher than the losses for the prinses Amalia wind farm is caused by the location and layout of the OWEZ wind farm. The OWEZ wind farm is more in the direction of the main wind resources seen from the HKZ location. Other reasons are that more wind turbines of the OWEZ wind farm have a free flow situation in the direction with the highest energy content while the prinses Amalia wind farm has more internal wake losses. Next to that the wind turbines at prinses Amalia wind farm have a lower hub height of 59 m while the hub height of the OWEZ wind farm is 70 m compared to the hub height of the wind turbines used to design the HKZ wind farms, of 108 m (8 MW) and 103 m (6 MW).

On the basis of a qualitative analysis of the effects calculated for the Borssele wind farm zone it is determined that the relative losses for the HKZ wind farms will increase with 45%:

- when the total installed capacity for the HKZ wind farms increases from 1400 MW to 2100 MW or when
- decreasing the available space for the HKZ wind farms with the area within the 12 mile zone.

On the basis of the available information it is not possible to estimate a combined effect of increasing the nominal power and decreasing the available area.

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Appendix A. The characteristics of the wind turbines

The wind turbine models used for the HKZ wind farms in the FARMFLOW analysis have the following power and axial force curve:

Table 9: The wind turbine power curve and axial force coefficient for the wind turbines used to model the HKZ wind farms

	6 MW 154 m wind turbine		8 MW 164 m wind turbine	
U [m/s]	P [kW]	C _T [-]	P [kW]	C _T [-]
3	0.	0.	0.	0.
4	268.	0.858	130.	0.816
5	585.	0.858	580.	0.775
6	1058.	0.858	1120.	0.78
7	1710.	0.857	1860.	0.782
8	2573.	0.858	2860.	0.782
9	3673.	0.857	4080.	0.783
10	4850.	0.804	5600.	0.783
11	5665.	0.607	7100.	0.783
12	5945.	0.418	7860.	0.523
13	5993.	0.316	7950.	0.388
14	6000.	0.248	7980.	0.302
15	6000.	0.201	7995.	0.241
16	6000.	0.165	8000.	0.197
17	6000.	0.138	8000.	0.164
18	6000.	0.117	8000.	0.138
19	6000.	0.100	8000.	0.118
20	6000.	0.087	8000.	0.102
21	6000.	0.076	8000.	0.088
22	6000.	0.067	8000.	0.078
23	6000.	0.06	8000.	0.069
24	6000.	0.053	8000.	0.061
25	6000.	0.048	8000.	0.055

Table 10: The wind turbine power curve and axial force coefficient for the wind turbines to model the OWEZ and Prinses Amalia wind farms

U [m/s]	V90 - 3MW OWEZ		V80 - 2 MW Prinses Amalia	
	P [kW]	C _r [-]	P [kW]	C _r [-]
3.2	0.	0.874	0.	0.818
4.	77.	0.874	66.6	0.818
5.	190.	0.836	154.	0.806
6.	353.	0.805	282.	0.804
7.	581.	0.805	460.	0.805
8.	886.	0.808	696.	0.806
9.	1273.	0.796	996.	0.807
10.	1710.	0.729	1341.	0.793
11.	2145.	0.658	1661.	0.739
12.	2544.	0.572	1866.	0.709
13.	2837.	0.494	1958.	0.409
14.	2965.	0.376	1988.	0.314
15.	2995.	0.296	1997.	0.249
16.	3000.	0.240	1999.	0.202
17.	3000.	0.199	2000.	0.167
18.	3000.	0.167	2000.	0.140
19.	3000.	0.142	2000.	0.119
20.	3000.	0.122	2000.	0.102
21.	3000.	0.105	2000.	0.088
22.	3000.	0.092	2000.	0.077
23.	3000.	0.081	2000.	0.067
24.	3000.	0.072	2000.	0.060
25.	3000.	0.064	2000.	0.053
25.5	1500.	0.0405	1000.	0.0335
26.	0.	0.	0.	0.

Table 11: The wind turbine power curve and axial force coefficient for the wind turbines used to model the Luchterduinen wind farm

V112 - 3MW Luchterduinen					
U [m/s]	P [kW]	C _T [-]	U [m/s]	P [kW]	C _T [-]
2.8	0	0.950	12.5	3000	0.343
3.0	12	0.950	13.0	3000	0.3
3.5	53	0.923	13.5	3000	0.265
4.0	121	0.899	14.0	3000	0.236
4.5	205	0.864	14.5	3000	0.211
5.0	303	0.836	15.0	3000	0.19
5.5	420	0.822	16.0	3000	0.156
6.0	559	0.817	17.0	3000	0.13
6.5	723	0.813	18.0	3000	0.11
7.0	914	0.809	19.0	3000	0.095
7.5	1133	0.804	20.0	3000	0.082
8.0	1383	0.800	21.0	3000	0.071
8.5	1662	0.795	22.0	3000	0.063
9.0	1972	0.788	23.0	3000	0.056
9.5	2299	0.764	24.0	3000	0.05
10.0	2595	0.714	25.0	3000	0.045
10.5	2805	0.636	25.3	1500	0.025
11.0	2951	0.549	25.5	0	0
11.5	2984	0.463			
12.0	2996	0.396			

Appendix B. The HKZ area's

Table 12: The coordinates, in UTM format, enclosing the area's

A) Site 1: 3 area's enclosed		B) Site2: 1 area enclosed	
X coordinate	Y coordinate	X coordinate	Y coordinate
576948.7	5808275	563073.9	5797188
576952.6	5808158	570003.9	5797059
575648.3	5805574	570376.5	5797159
572930.6	5807051	571344.5	5791559
572804.4	5807112	564370.2	5789770
576948.7	5808275	562982.7	5796693
		563073.9	5797188
572197.7	5806063		
572589.3	5806099		
579083.4	5802568		
578933.5	5802214		
578854.4	5802196		
571707.3	5805216		
572197.7	5806063		
570241.5	5804750		
577182.7	5801816		
568076.4	5799744		
563545.3	5799743		
564404	5804398		
570241.5	5804750		

C) Site 3: 2 area's enclosed

X coordinate	Y coordinate
571654.4	5790608
575586.6	5789003
575295.7	5788618
574628.8	5788129
574056.7	5787680
573443.8	5787155
572912.4	5786661
572228.2	5785964
572174.6	5785904
565761.4	5789096
571654.4	5790608
564614.8	5788549
571496.2	5785124
570998.7	5784499
570303.3	5783529
569557.2	5782954
569045.5	5782533
568540.7	5782087
567997.4	5781570
565470.5	5784280
564614.8	5788549

D) site 4; 7 area's enclosed.

X coordinate	Y coordinate
582711.5	5808743
582767	5808738
582611	5806261
581587.2	5806582
581882.3	5807211
582211.3	5807858
582711.5	5808743
583763.5	5808650
585589.4	5808488
585497.2	5808226
585050.6	5807048
584618.3	5805978
584467	5805571
584346.5	5805691
584209.9	5805758
583593.5	5805952
583763.5	5808650
581193.4	5805658
582546.5	5805233
582476.5	5804059
582497.8	5803883
580316.8	5803383
580760.7	5804487
580994.8	5805140
581193.4	5805658
583529.2	5804924
583723.5	5804863
583970.3	5804432
583868.3	5804198
583479.4	5804109
583529.2	5804924
580431.8	5801531
582771.2	5802064
582791.4	5801929
580662.8	5801433
580431.8	5801531
571805	5798693
573716.5	5799154
577973.7	5800133
578941.5	5800386
580945.7	5799595
581914.7	5799822
581622.3	5799242
581211.5	5798487
580957.2	5797992
579824	5797873
579044.1	5797825
578245.8	5798345
577189.5	5798420
576205.4	5798446
576009	5798493
571790.9	5798626

571805	5798693
571716.1	5797628
575794.3	5797499
575995.6	5797451
577140.2	5797421
577918.9	5797366
578774.1	5796806
579910.6	5796877
580427.9	5796931
580393.7	5796862
579898.9	5795803
579248.3	5794721
578876.2	5794024
578378.3	5793015
577806.7	5792061
576959	5790899
576572.1	5790328
573472.2	5791607
572710	5791903
571716.1	5797628

Appendix C. Lay out of the existing wind farms

Table 13: The lay-out of the OWEZ Wind Farm, in UTM coordinates, consisting of 36 Vestas V90-3MW with a hub height of 70 m.

Turbine	X	Y	Turbine	X	Y
#	[m]	[m]	#	[m]	[m]
1	597181.9	5826380	19	595384.9	5829940
2	596756.9	5826863	20	594959.9	5830424
3	596339.9	5827338	21	594534.9	5830908
4	595914.9	5827822	22	598548.9	5827853
5	595490.9	5828305	23	598119.9	5828338
6	595065.9	5828789	24	597695.9	5828826
7	594633.9	5829281	25	597038.9	5829572
8	594208.9	5829764	26	596560.9	5830116
9	593783.9	5830248	27	596135.9	5830600
10	593366.9	5830739	28	595710.9	5831084
11	592933.9	5831216	29	595285.9	5831568
12	592508.9	5831700	30	598868.8	5828998
13	598189.9	5826748	31	598446.9	5829486
14	597764.9	5827232	32	597796.9	5830224
15	597339.9	5827715	33	597312.9	5830776
16	596914.9	5828199	34	596887.9	5831260
17	596234.9	5828973	35	596462.9	5831744
18	595809.9	5829457	36	596037.9	5832228

Table 14: The lay out of the Prinses Amalia Wind Farm, in UTM coordinates, consisting of 30 Vestas V80-2MW wind turbines with a hub height of 59 m.

Turbine	X	Y	Turbine	X	Y
#	[m]	[m]	#	[m]	[m]
1	580549	5826228	31	584439	5827608
2	581045	5825990	32	584906	5827318
3	581541	5825752	33	585373	5827027
4	582037	5825515	34	581587	5828734
5	582483	5826385	35	582059	5828452
6	582970	5826130	36	582531	5828170
7	583457	5825875	37	583004	5827888
8	583944	5825620	38	583476	5827606
9	584432	5825365	39	583948	5827323
10	580529	5826802	40	584420	5827041
11	581021	5826556	41	584892	5826759
12	581513	5826310	42	585364	5826477
13	582004	5826064	43	581070	5828385
14	582496	5825818	44	581547	5828111
15	582988	5825571	45	582026	5827839
16	583480	5825325	46	582502	5827566
17	584024	5829007	47	582980	5827293
18	583073	5829056	48	583457	5827020
19	583534	5828757	49	583934	5826747
20	583996	5828458	50	584412	5826473
21	584457	5828159	51	582490	5826971
22	582105	5829063	52	582972	5826707
23	582572	5828772	53	583454	5826443
24	583039	5828481	54	583937	5826179
25	583505	5828191	55	584419	5825915
26	583972	5827900	56	584902	5825651
27	584889	5826200	57	580533	5827405
28	581043	5827763	58	581021	5827150
29	581525	5827499	59	581508	5826895
30	582007	5827235	60	581995	5826640

Table 15: The lay-out of the Luchterduinen wind farm, in UTM coordinates, consisting of 43 V112-3MW wind turbines with a hub height of 81 m.

Turbine	X	Y	Turbine	X	Y
#	[m]	[m]	#	[m]	[m]
1	578089	5808005	25	577459	5805566
2	580868	5807450	26	576928	5805849
3	580393	5807703	27	579890	5805212
4	579918	5807955	28	579373	5805487
5	579443	5808207	29	578856	5805762
6	578969	5808460	30	578338	5806037
7	578494	5808712	31	577821	5806312
8	581238	5808169	32	577304	5806588
9	580641	5808486	33	580183	5805968
10	580145	5808749	34	579679	5806236
11	579649	5809013	35	579176	5806503
12	581602	5808840	36	578673	5806771
13	580592	5809287	37	578170	5807039
14	581921	5809650	38	577667	5807306
15	579283	5803658	39	580525	5806709
16	578738	5803948	40	580038	5806968
17	578192	5804238	41	579551	5807227
18	577646	5804529	42	579064	5807486
19	577101	5804819	43	578576	5807745
20	576555	5805110			
21	579585	5804435			
22	579054	5804718			
23	578522	5805000			
24	577991	5805283			

Appendix D. FarmFlow

For the accurate prediction of wind turbine wake effects in (large) offshore wind farms, ECN has developed the software tool . FARMFLOW calculates the average velocities and turbulence levels inside a wind farm. A boundary layer model is used for the calculation of the free stream wind speed and can be used for assessments for different atmospheric stability conditions. Currently FarmFlow is extended to include an assessment of mechanical loads on the wind turbines.

For the validation of FARMFLOW, a large amount of accurate experimental data from Nordex N80 2.5MW wind turbines from ECN Wind Turbine test station Wieringermeer (EWTW) has been used. Additionally, experimental data from three large offshore wind farms have been applied.

The calculated wake velocity deficits and turbulence intensities agree very well with experimental data for all wind speeds and ambient turbulence intensities. Excellent agreement between calculated and measured turbine performance is found. FARMFLOW tends to slightly overestimate the generated turbulence intensity.

The wake model in FARMFLOW is based on a 3D parabolised Navier-Stokes code, using a k-epsilon turbulence model to account for turbulent processes in the wake. The ambient flow is modelled in accordance with the method of Panofsky and Dutton³. The free stream wind as a function of height is calculated for a prescribed ambient turbulence intensity and Monin-Obukhov length, which takes the atmospheric stability into account.

³ Atmospheric turbulence: models and methods for engineering applications / Hans A. Panofsky, John A. Dutton

ECN

Westerduinweg 3

1755 LE Petten

The Netherlands

P.O. Box 1

1755 LG Petten

The Netherlands